# PARTIAL-OVERLAP BIOCULAR IMAGE MISALIGNMENT TOLERANCE STUDIES

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## ABSTRACT

Partial-overlap biocular head/helmet-mounted display (HMD) design flexibility, cost, and utility are directly related to allowed image misalignment maximums. Currently, suggested standards are based on highly variable data from a number of studies. They do not usually account for visual problems of users, particularly if the problems fall outside results of routine eye exams or current regulatory standards. This study tested the suggested standards for divergent horizontal and relative vertical image misalignments in a partial-overlap biocular optical system.

Post-data-collection, pre-data-analysis vision diagnoses, where appropriate, were determined from an initial clinical eye exam given to each subject. The diagnoses were compared to the number of vigilance errors, occurrence of diplopia, number of no-responses, and number of indicated suppressions while viewing misaligned symbology seen against a simulated natural background. It should be noted that the diagnoses obtained from the initial eye exam would not have removed subjects from flight status, based on U. S. Army regulations (Department of the Army, 2002). Nevertheless, individuals diagnosed with accommodation[1] and/or vergence[2] problems clearly showed reduced visual performance on divergent horizontal misalignments when compared to controls. Subjects with accommodative and/or vergence vision problems that were presented vertical misalignments did not show a similar decline in performance. No significant differences in visual performance were obtained for initial, individual clinical test measurements falling outside one standard deviation (SD) of the norm--for either vertical or horizontal misalignments.

Statistical significance of pre-versus-post in-device optometric and out-of-device vergence facility measurements was also discussed. These results showed that divergent horizontal misalignment near, but not at, the recommended maximum significantly stressed the accommodative and vergence systems. Control subjects, treated in the same way as experimental subjects, but without image misalignment, did not show significant accommodative and vergence stress.

## 1. INTRODUCTION

Biocular or binocular HMDs are becoming a technology of choice in an increasingly wide range of military applications. These include field training and simulation, remote sensing and unmanned vehicle control, head-up instrument display, and target designation (Melzer, 2002). They provide the advantages of vision with two eyes, namely improved clarity, stereopsis, reduced binocular rivalry, and a wide field-of-view (FOV). They often are lighter, more easily transported, and more rugged than other types of displays, while doing the same job. However, they also have the disadvantages of increased complexity, increased head weight and bulk, alignment problems, and higher cost (when compared to conventional displays).

This paper presents the first in a series of studies being conducted at the U. S. Army Aeromedical Research Laboratory, Fort Rucker, AL, intended to establish U. S. Army standards for image misalignment tolerance in biocular or binocular HMDs. Design flexibility, user performance, head supported weight and bulk, and production cost are all directly related to image misalignment maximums. Currently, suggested standards are based on highly variable data from a number of studies, most using subjective discomfort or diplopia as the dependent variable (Rash, 1998; Melzer and Moffitt, 1997; Self, 1986). In fact, all researchers do not even interpret similar results in the same way (Peli, 1998; Howarth and Costello, 1997; Mon-Williams et al., 1993). None of these studies investigate the relation between vision diagnosis and performance while using an HMD.

[1] Accommodation is the complicated process of focusing images.
2 Vergence is the coordinated movement of the eyes in opposite directions to maintain single vision.

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Partial-overlap HMDs with see-through biocular symbology, developed for daytime application, are the most visually demanding of these technologies. Consequently, this optical system was simulated and served as our initial test-bed. Horizontally and vertically misaligned symbology was seen against a computer-generated natural background through two telescopes. Divergent horizontal misalignment values, at or near those recommended by Melzer (2002) and Melzer and Moffitt (1997), were tested (suggested relative vertical tolerances from 0.9 - 1.8 mrad; divergent horizontal tolerance at 0.9 mrad). All subjects in this study passed the visual requirements for flight school. The majority were individuals awaiting flight school, although a few were active pilots and civilians. Vision diagnoses, based on an initial clinical exam, and in-device optometric measurements (pre-, post-, and during-misalignment) were related to visual performance on vigilance tasks.

## 2. BACKGROUND

Natural vision is generally seamless and taken for granted. We are well-adapted to the visual environment in which we normally operate. Images from the two eyes are easily fused. There is a built-in adaptability of the nervous system compensating for small variations in images from the two eyes that we normally confront (size, shape, color, luminance, registration). Divergence and convergence of the two eyes combine with accommodation to make distant and near objects single and clear.

Vision in HMDs is not, however, like natural vision. Variations in focus and convergence of the two eyes, that we normally associate with object distance, are usually absent or conflicting. Registration of images on the two retinas can easily be outside normal tolerances, as with divergent horizontal disparities. Distortions imposed by HMD optics can make fusion difficult or impossible. Lag times between virtual and real events or movements can be disconcerting and fatiguing. Visual symptoms have included eye fatigue, headache, double vision, blurred vision, illusions, and impaired depth perception (Kalich et al., 2003, 2004; Melzer and Moffitt, 1997; Peli, 1996, 1995; Mon-Williams et al., 1993; McLean and Smith, 1987). What, then, are the tolerances that minimize discomfort or loss in visual or cognitive performance?

Self (1986) wrote one of the most influential papers on misalignment tolerance, reviewing studies through the mid 1980s. Several of the early papers and military standards on optical and image misalignment, usually with respect to binoculars, did not provide or reference methods, data, or sources. The problem was later addressed systematically in the context of head-up display (HUD) research. Self found divergent horizontal and relative vertical tolerance recommendations varying from 1 to 4 milliradians (mrad). Lippert (1990) suggested a vertical misalignment tolerance of 5.6 mrad. The suggested tolerance standards recommended by Melzer and Moffitt (1997), and referenced by Melzer (2002), had the narrowest ranges for any of the misalignment types, reflecting the low misalignment tolerance and sharp cut-offs seen by Gibson (1980).

Mallett (1974); Jenkins, Pickwell and Abd-Manan (1992); and later Mon-Williams, Wann and Rushton (1993) and Mon-Williams and Wann (1998) showed visual changes that were related to ocular symptoms and binocular stress: post-HMD headache, double vision, blurred vision, sore eyes and eye strain. Howarth (1996) investigated the effect of varying vergence demand while maintaining a constant accommodative demand. He found adaptive changes to prism, heterophoria[3], and some symptoms, including headache and ocular discomfort (although many subjects did not report discomfort). In a more recent paper, Howarth (1999) further evaluated the causes of heterophoria change using three commercial HMD systems. He concluded that Wann, Rushton and Mon-Williams (1995) and Rushton, Mon-Williams and Wann (1994) incorrectly attributed changes in heterophoria to using a stereoscopic HMD. Howarth concluded that heterophoria changes were idiosyncratic to the particular HMD used and not to type of HMD. Howarth and Costello (1997) investigated a simulation, using a lightweight HMD, in which subjects detected head movements through their vestibular system, but did not receive corresponding visual feedback. The same subjects viewed a video display unit for a corresponding period of time. Results were compared and HMD simulation produced a significantly greater frequency of general discomfort, fatigue, headache, nausea, dizziness, stomach awareness, and hot or burning eyes.

Peli (1998) compared HMD and desktop cathode ray tube (CRT) display use. While he found visual changes similar to those of Mon-Williams, Wann, and Rushton (1993) and Howarth and Costello (1997), his conclusions were quite different. Results from watching a 30-minute game on an HMD and control desktop CRT were indistinguishable. Peli (1998) stated that none of the measurable changes in the accommodative and vergence systems associated with HMD use seemed to be permanent, although resulting visual discomfort and double vision were possible. Similarly, measurable changes in vision can occur from daily stresses. Yekta, Jenkins and Pickwell (1987) found changes in vision at the end of the workday associated with an increased visual discomfort.

[3] Heterophoria is the deviation of the eyes only when there is no stimulus for fusion. Normally both eyes will point toward an object and fuse corresponding retinal images.

There is a wealth of information, some of it contradictory, relating HMD use to subjective impressions, specific visual measurements and visual symptoms. There are fewer studies that relate HMD use to performance on tasks requiring vision (McLean and Smith, 1987). And, there are even fewer studies relating image misalignment in partial-overlap biocular optical systems to visual measurements, specific vision diagnoses, and performance on visual tasks (Kalich et al., 2004, 2003; Rash, 1998; Melzer and Moffit, 1997; Self, 1986). Three questions were addressed in this study. First, are there measurable changes in vision attributable to image misalignments in a partial-overlap biocular display, above and beyond those expected from an aligned display? Second, are there measurable decrements in performance on a visual task attributable to image misalignments near current recommended maximums? And, third, are there measurable decrements in performance predictable from a routine eye exam when there are image misalignments near current recommended values?

## 3. METHOD

### 3.1 Subjects

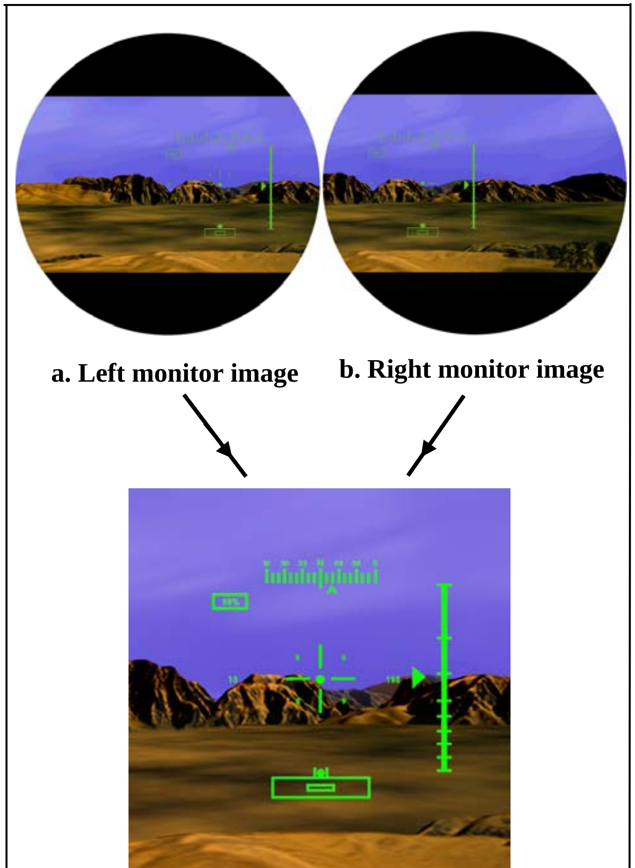
Twenty-four experimental and twelve control subjects were recruited and participated in this study. They were primarily U. S. Army aviation pilot candidates awaiting training, although a few were rated aviators or civilians. All flight candidates had passed the vision requirements for flight training (Table). Most subjects were male, but five were female. None wore spectacles, one wore contact lenses.

**Table. Vision Requirements For Army Flight Training (Department of the Army, 2002)**

- Uncorrected distance and near Snellen visual acuity for each eye not worse than 20/50
- Corrected distance and near Snellen visual acuity for each eye not worse than 20/20$^{-1}$
- Astigmatism within ±1 diopter (D) cylinder
- Hyperopia (far sightedness) not in excess +3.00 D sphere
- Myopia (near sightedness) not in excess of -1.50 D sphere
- Esophoria or exophoria not > 8 prism diopter
- Hyperphoria not > 1 prism diopter

### 3.3 Instrumentation

Each subject was given an initial optometric exam. Standard instrumentation and procedures were employed (Benjamin, 1998; Carlson et al., 1996), except for an Armed Forces Vision Tester, used for visual acuities, heterophorias, and stereopsis. Subject diagnoses were based on this exam.



**a. Left monitor image** **b. Right monitor image**

**c. Fused image center (the lines are artificially enhanced for clarity)**

**Fig. 1 Images a and b were presented to the left and right eye respectively during the 6-minute experimental task. The subject fused the images at the symbology center, producing a partially overlapping image; i.e., the center was biocular, and the left and right periphery was monocular, laterally extending the FOV. The symbology was the same in both images, except at the center. The two upper numbers, in the upper left and right crosshair quadrants, were presented to the left eye, along with the upper-vertical and left horizontal lines. The two lower numbers, and the right and lower-vertical lines, were presented to the right eye. Horizontal offset of the symbology was incremented in the right eye, with number positions remaining constant with respect to the background. Vertical offset symbology, presented to the left and right eye were moved up and down respectively. Image c shows how the fused symbology would look to a subject.**

The experimental optical system produced a 67.4° horizontal and 29.3° vertical biocular FOV with a partial overlap of 32.8°. Computer-generated imagery was seen through two telescopes (produced by separating a Nikon 7x50 Prostar binocular). Two multicoated, 2-element Pentax 0.44 D achromatic correcting lens were used in front of each objective. They set the two Eizo PlexScan F980 CRT monitors to optical infinity. Each monitor had an active display of 1600 H x 1200 V pixels averaging 0.245 mm center-to-center separation. Images were generated using a Dell 530 Workstation with Radian VE dual monitor video card (Figure 1). The two images were color matched. The optical system was a periscope-like design (Figure 2). The observed pixel count within each image was 696 Hx780 W.

**Fig. 2 The in-device optical setup for optometric tests and experimental misalignment tasks. It simulates a see-through, daytime, partial-overlap biocular HMD**

The lime green symbology had a screen luminance of 7.6 foot-lamberts (fL). The mostly brown and blue background varied from 0.08 fL to 10 fL. Divergent horizontal symbology misalignments with respect to background were 1.5 mrad (level 1--5.1 minutes arc) or 3.7 mrad (level 2—12.7 minutes arc). Relative vertical misalignments were 2.2 mrad (level 1—7.6 minutes arc) or 4.5 mrad (level 2--15.3 minutes arc). Control subjects had no misalignment.

The out-of-device vergence facility target and in-device pre- and post-misalignment optometric test figures are shown in Figure 3. A separate computer and monitor were used for the vergence facility test. The in-device tests were all done within the overlapping or biocular portion of the FOV. The luminance of the in-device monitor screen approximated that of the over-all symbology-background image. A 1-minute, 5.0 fL, gray adapting field was presented before the pre- and post-in-device optometric tests and prior to the 6-minute symbology-background presentation.

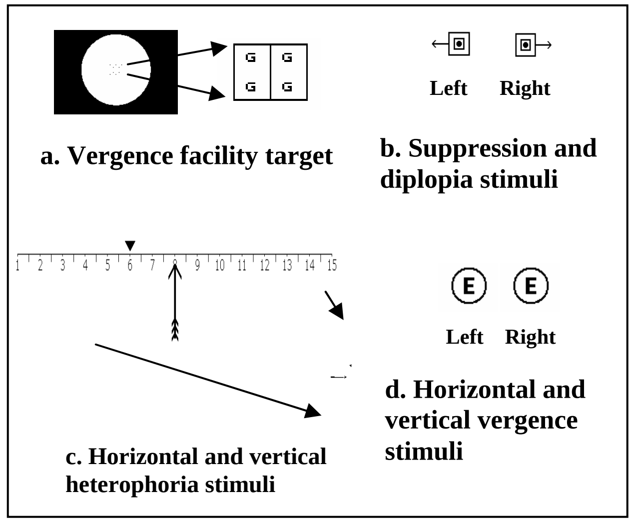



**Fig. 3 Automated out-of-device vergence facility target and in-device optometric test figures. A separate computer controlled the vergence facility target. Following a prism change, letters or numbers were presented as all-the-same or different, requiring the subject to designate correctly when the image was single and clear.**

Eye position, interpupillary distance, optics, and monitor position were fully adjusted to each subject. Each telescope was set to compensate for instrument myopia (-0.5 D with corresponding convergence). Subject responses were made using a joystick. Responses during symbology-background presentation were cued 20 times per 2 minutes in a pseudo-randomized fashion with an auditory stimulus (2 minutes without misalignment, followed by 2 minutes with misalignment, followed by 2 minutes without misalignment).

### 3.2 Procedures

The experimental session for each subject lasted 3-4 hours. A vision exam and task training followed informed consent discussion. This exam was used to determine whether a subject met basic study vision requirements. Following the exam, the subject was assigned a type of misalignment (divergent horizontal, relative vertical, or control) and level-of-misalignment sequence in a pseudo-random fashion (larger offset during trial 1 and smaller offset during trial 2, or smaller first with larger second). A full practice trial (trial 1) without misalignment was conducted following a 10-minute break. After this first trial, there was a questionnaire and discussion. A second break was followed by an experimental trial (trial 2), a break, and another experimental trial (trial 3). A questionnaire and brief discussion also followed the experimental trials. Each trial, including the practice trial, lasted about 20 minutes. Each was preceded and followed by the out-of-device

vergence facility test, in-device adaptation field, and the in-device optometric tests. The 6-minute experimental period was identical for each subject in each trial, except for type and magnitude of misalignment (presented during the middle 2 minutes). Subjects were not cued when the misalignment occurred. Control subjects were not presented a misalignment during the middle 2 minutes. Each experimental subject was presented with two levels of only one type of alignment, one level during trial 2 and one level during trial 3.

## 4. DATA ANALYSIS AND RESULTS

The Kruskal-Wallis one-way analysis of variance was used to test whether the three independent misalignment samples were drawn from different populations. Since all subjects had been treated identically through the first 2-minute experimental period of trial 2 (no misalignment), the dependent variables from the first part of trial 2 were compared. The hypothesis was rejected at $p<0.46$ for vigilance errors. Similar probabilities were obtained for the optometric tests. The alternative proposition was accepted, that they were drawn from the same population.

Automated out-of-device vergence facility significantly declined following level 2 divergent horizontal misalignment (Figure 4). This was a decline in ability to alternate convergence and corresponding accommodation with divergence and corresponding accommodation. However, there was no significant decline in facility following level 1 divergent horizontal misalignment, nor following levels 1 or 2 relative vertical misalignment, nor following the control no-misalignment condition.

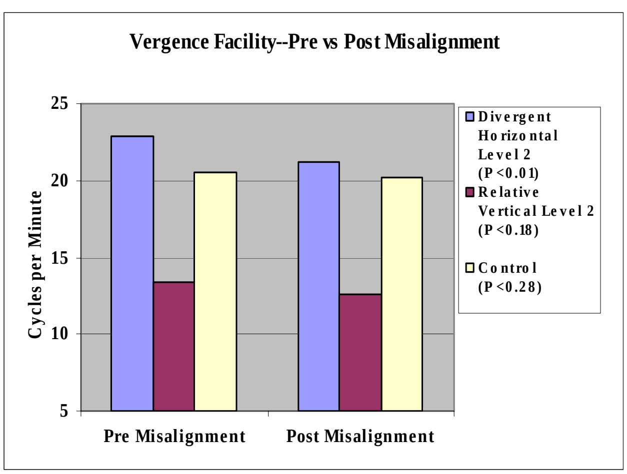



**Fig. 4 Significance of post-misalignment vergence facility reduction was determined using the Wilcoxon matched-pairs test.**

As the retinal disparity of two images increases, it becomes harder to maintain clear, single vision. The point where the fused image breaks into two is called the break. By reducing the disparity, a point is reached when a double image can again be fused. This is called the recovery. In this study, there was a significant reduction in the in-device divergence disparity that could be re-fused (recovery) following level 2, but not level 1 of both divergent horizontal and relative vertical misalignments (Figures 5 and 6). Level 2 divergent horizontal misalignment convergence break-recovery was significant, but not level 1 (Figure 5). Neither level was significant for the relative vertical misalignments (Figure 6). This measure was most sensitive to an early break There was no significant, corresponding reduction in

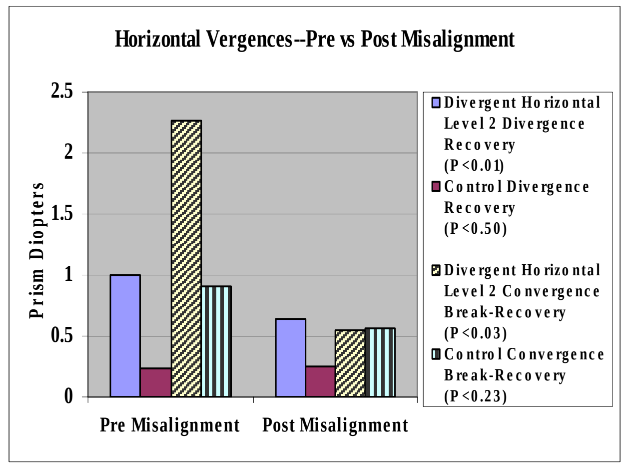



**Fig. 5 The significance of reduced post divergent horizontal misalignment and control no-misalignment divergence recovery and break-recovery was determined using the Wilcoxon matched-pairs test.**

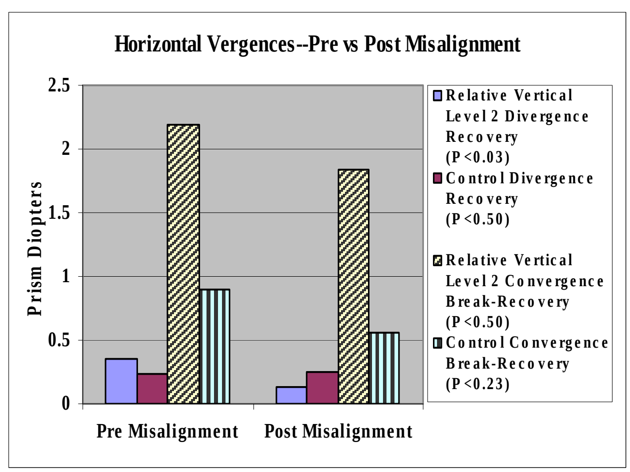



**Fig. 6 The significance of reduced post relative vertical misalignment and control no-misalignment divergence recovery and break-recovery was determined using the Wilcoxon matched-pairs tests.**

either recovery or break-recovery for the controls (Figures 5 and 6). This was a strong indication that misalignment creates visual stress.

As shown above, measurements of vergence and accommodation are sensitive indicators of misalignment stresses on the visual system. This is further supported by the data relating diagnoses, determined from the initial vision exam, to measures of visual performance during misalignment. In order to maintain objectivity, the diagnoses were determined from numbered files after data collection and prior to data analysis. In order to maintain consistency of diagnosis, three separate diagnosis passes, using preestablished criteria, were made by two optometrists.

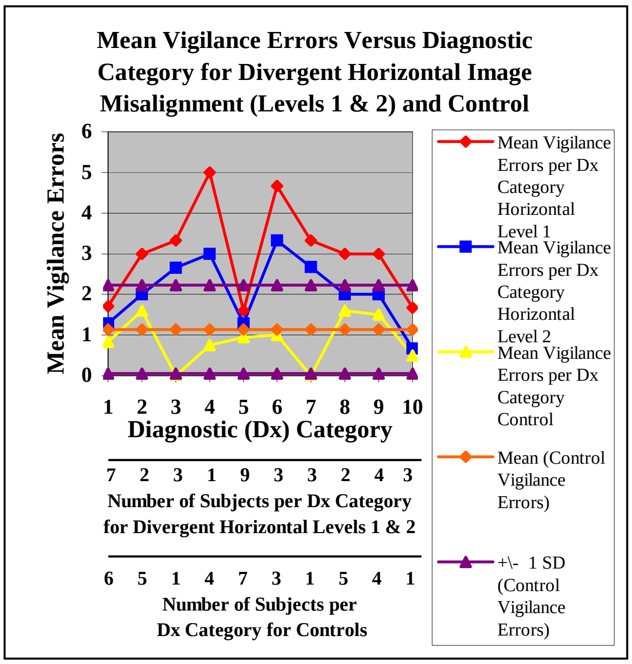



**Fig. 7 Diagnostic categories are compared to mean vigilance errors obtained during the presentation of level 1 and level 2 divergent horizontal image misalignments. Diagnostic categories listed here are: 1) AC/A 4-7, 2) AC/A <4, 3) AC/A > 7, 4) combined accommodative spasm and ill-sustained accommodation, 5) astigmatism (all types combined), 6) combined convergence insufficiency and convergence excess, 7) high near esophoria, 8) high near exophoria, 9) latent hyperopia, and 10) hyperphoria. These categories are not mutually exclusive. The same subject can be in more than one category. The number of subjects in each category is given on the bottom 2 axes.**

Diagnostic category was related to four measures of visual performance during misalignments: number of vigilance errors, occurrence of diplopia, number of no-responses (within a 2-second period following an auditory cue), and number of indicated visual suppressions. Level 1 and level 2 measurements for each type of misalignment were combined and a mean calculated. Only one measure is shown here. However, these data (Figures 7 and 8) are representative of results obtained from the suppression, no-response, and diplopia measures.

There were 20 separate vision tests given in the initial vision exam, providing convergent data for diagnosis. None of these separate tests were significantly related to performance on vigilance tasks during any of the image misalignments. Figures 9, 10 and 11 are representative of these data and show the relation between near-point-of-

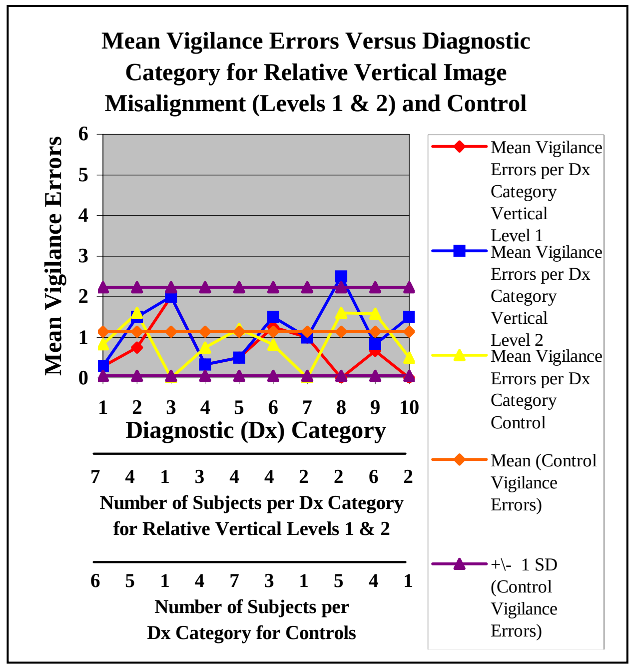



**Fig. 8 Diagnostic categories are compared to mean vigilance errors obtained during the presentation of level 1 and level 2 relative vertical image misalignments. Diagnostic categories are listed in Figure 7.**

convergence and mean vigilance errors during the first 2 minutes (no misalignment) and the second 2 minutes (misalignment) of the experimental task. Near point of convergence determines the break point for convergence (distance from the eye at which one first sees two images) and the recovery point (distance from the eye at which one is first able to fuse a diplopic image). The categories for the near-point-of-convergence are based on normative standards (Benjamin, 1998; Carlson et al., 1996).

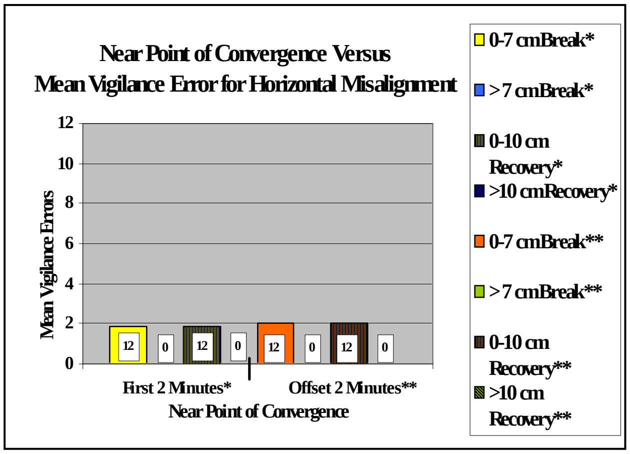



**Fig. 9 The numbers inside each box, within or above a bar, show the number of subjects in that category. Differences were tested using Wilcoxon matched-pairs tests. None were significant. However, there were too few vigilance errors to obtain meaningful statistical comparisons.**

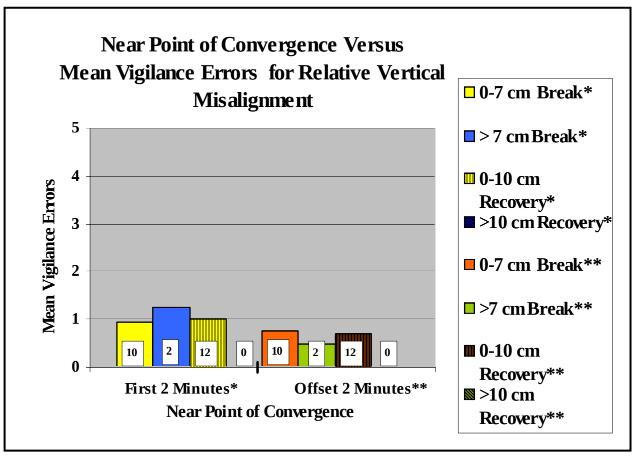



**Fig. 10 The numbers inside each box, within or above a bar, show the number of subjects in that category. There were too few vigilance errors to obtain meaningful statistical comparisons.**

## 5. CONCLUSIONS

There are two main conclusions to be drawn from this study. First, accommodative and/or convergence problems diagnosed from a clinical exam are associated with reduced performance on a vigilance task during divergent horizontal misalignments near, but not at, currently recommended tolerance levels. It should be noted that similar results were not obtained for relative vertical misalignments. This makes sense, as there is not a corresponding accommodative-vergence mechanism for vertical eye movements that helps to maintain single

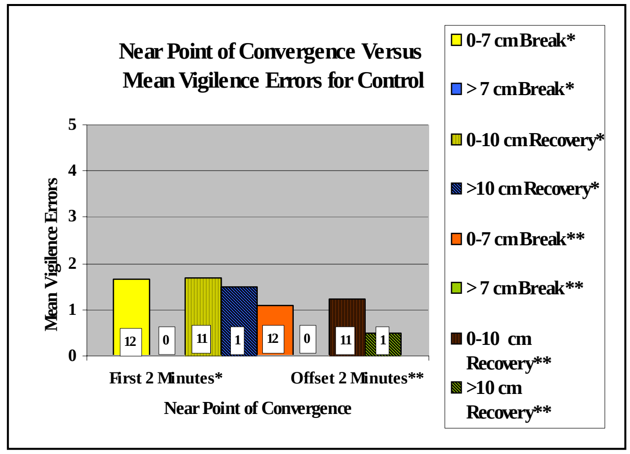



**Fig. 11 The numbers inside each box, within or above the bar, show the number of subjects in that category. Differences were tested using Mann-Whitney U tests. None were significant.**

vision, although horizontal and vertical mechanisms can interact. Effects of problems like hyperphoria, a vertical alignment problem, may not show up during short exposures to image misalignment.

Second, there are specific in-device accommodation and vergence measures sensitive to misalignment alone. Vergence facility, the ability to repeatedly diverge-accommodate and converge-accommodate the eyes, was sensitive to level 2 divergent horizontal misalignment, but not to either level of vertical misalignment or to no-misalignment. Convergence break-recovery was significant only for level 2 horizontal misalignment.

We did not find a specific clinical measurement associated with an increase in vigilance errors during image misalignment. This would be expected from a small-sample of mostly young pilot candidates. The question of individual clinical-test predictors remains open.

The next study in this series will look at pre- and post-misalignment measurements of saccades and pupil lag times using the Functional Impairment Tester (Russo, 1999). These measurements are quick and the device compact. Studies on the impact of other types of misalignment and HMD wearing-time will follow.

## DISCLAIMER

The views, opinions, and/or findings contained in this paper are those of the authors and should not be construed as an official Department of the Army position or decision unless so designated by other official documentation.

## REFERENCES


Benjamin, W.J. (ed.), 1998: *Borish's Clinical Refraction*, W.B. Saunders Company, Philadelphia, 1255.

Carlson, N.B., Kurtz, D., Heath, D.A. and Hines, C., 1996: *Clinical Procedures for Ocular Examination. 2nd Ed*, Appleton & Lange, Stamford, CT, 493.

Department of the Army, 2002: *Standards of Medical Fitness*, Washington, DC.

Gibson, C.P., 1980: Binocular Disparity and Head-Up Displays, Human Factors, **22(4)**, 435-444.

Howarth, P.A., 1996: Empirical Studies of Accommodation, Convergence, and HMD Use, In *Proceedings of the Hoso-Bunka Foundation Symposium*, **December,** Tokyo. <http://www.lboro.ac.uk/departments/hu/groups/viserg/hosobunk.htm>

Howarth, P.A., 1999: Oculomotor Changes Within Virtual Environments, Applied Ergonomics, **30**, 59-67.

Howarth, P.A. and Costello, P.J.,1997: The Occurrence of Virtual Simulation Sickness when an HMD was Used as a Personal Viewing System, Displays, **8**, 107-116.

Jenkins, T.C.A., Pickwell, L.D. and Abd-Manan, F., 1992: Effects of Induced Fixation Disparity on Binocular Visual Acuity., Ophthal. Physiol. Opt., **12**, 299-301.

Kalich, M.E., Rash, C.E. van de Pol, C, Rowe, T.L., Lont, L. M. and Peterson, R. D., 2003: Biocular Image Misalignment Tolerance, In *Helmet- and Head-Mounted Displays VIII: Technologies and Applications, Proceedings of SPIE, Vol.* ***5079***, Bellingham, WA., 284-295.

Kalich, M.E., Lont, L. M., van de Pol, C., and Rash, C.E., 2004: Partial-Overlap Biocular Image Misalignment Tolerance, In *Helmet- and Head-Mounted Displays IX: Technologies and Applications, Proceedings of SPIE, Vol.* ***5442***, Bellingham, Washington, 261-272.

Lippert,, T.M., 1990: Fundamental Monocular/Binocular HMD Human Factors, In *Helmet-Mounted Displays II: Proceedings of SPIE, Vol.* ***1290***, Bellingham, Washington, 185-191.

Mallett, R. F.J., 1974: Fixation Disparity—Its Genesis and Relation to Asthenopia, The Ophthalmic Optician, **November**, 1159-1168.

McLean, W.E., and Smith, S., 1987: Developing a Wide Field of View HMD for Simulators, In *Display System Optics*, *SPIE Vol. 778*, Bellingham. WA, 79-82.

Melzer, J.E., 2002: *Head-mounted displays: Design and Applications. SPIE Short Course Notes* ***SC 159***, SPIE, Bellingham, WA.

Melzer, J.E. and Moffitt, K.,1997: *Head-Mounted Displays: Designing for the User*, McGraw-Hill, New York, 1997.

Moffitt, K., 1997: Designing HMDs for Viewing Comfort, In J.E. Melzer and K. Moffitt, *Head Mounted Displays: Designing for the Us*er, McGraw-Hill, New York, 117-145.

Mon-Williams, M. and Wann, J. P., 1998: Binocular Virtual Reality Displays: When Problems Do and Don't Occur, Human Factors, **40(1)**, 42-49.

Mon-Williams, M., Wann, J.P. and Rushton, S., 1993: Binocular Vision in a Virtual World: Visual Deficits Following the Wearing of a Head-Mounted Display. Ophthal. Physiol. Opt., **13(4)**, 387-391.

Peli, E. 1998: The Visual Effects of Head-Mounted Display (HMD) Are not Distinguishable from those of Desk-Top Computer Display. Vision Research, **38**, 2053-2066.

Peli, E., 1996: *Visual, Perceptual, and Optometric Issues with Head Mounted Displays (HMD). Seminar* ***M-10*** *Lecture* Notes, *Society for Information Display, Vol. 2*, May 13, M-10/3 – M-10/29.

Peli, E., 1995: Real Vision & Virtual Reality, Optics and Photonics News, **July**, 28-34.

Rash, C.E. (Ed.), 1998: *Helmet-mounted displays: Design issues for rotary-wing aircraft*. Army Aeromedical Research Laboratory, Fort Rucker, Alabama, 293.

Rushton. S., Mon-Williams, M., and Wann, J. P., 1994: Binocular Vision in a Bi-Ocular World: New Generation Head-Mounted Displays Avoid Causing Visual Deficits, Displays, **15**, 255-260.

Russo, M.B., 1999: Saccadic Velocity and Pupil Constriction Latency Changes in Partial Sleep Deprivation, and Correlations with Simulated Motor Vehicle Crashes, Sleep, **22(1; Supplement)**, 297.

Self, H.C., 1986: *Optical Tolerances for Alignment and Image Differences for Binocular Helmet-Mounted Display*, **AAMRL-TR-86-109**, Armstrong Aerospace Medical Research Laboratory, Dayton, OH, 35.

Yekta, A. A., Jenkins, T. and Pickwell, D., 1987: The Clinical Assessment of Binocular Vision Before and After a Working Day, Ophthal. Physiol. Opt., **7(4)**, 349-352.

Wann, J.P., Rushton, S. and Mon-Williams, M., 1995: Natural Problems for Stereoscopic Depth Perception in Virtual Environments, Vision Research, **35(19)**, 2731-2736.